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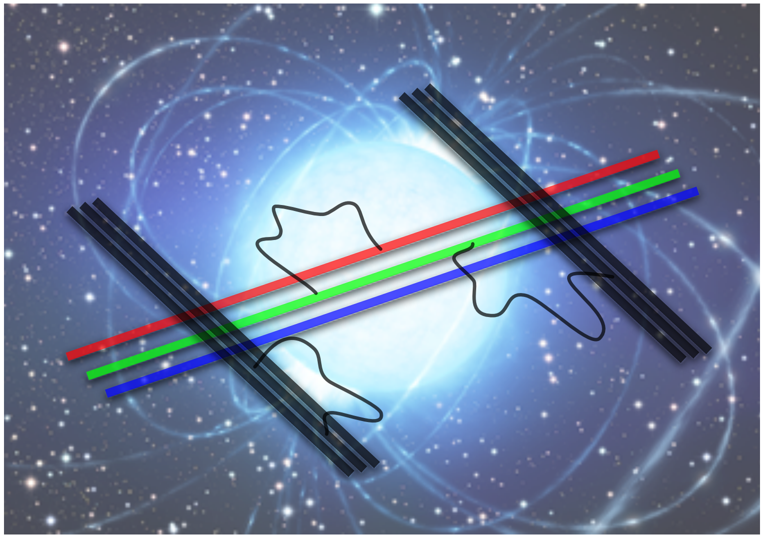
STAG RESEARCH CENTRE

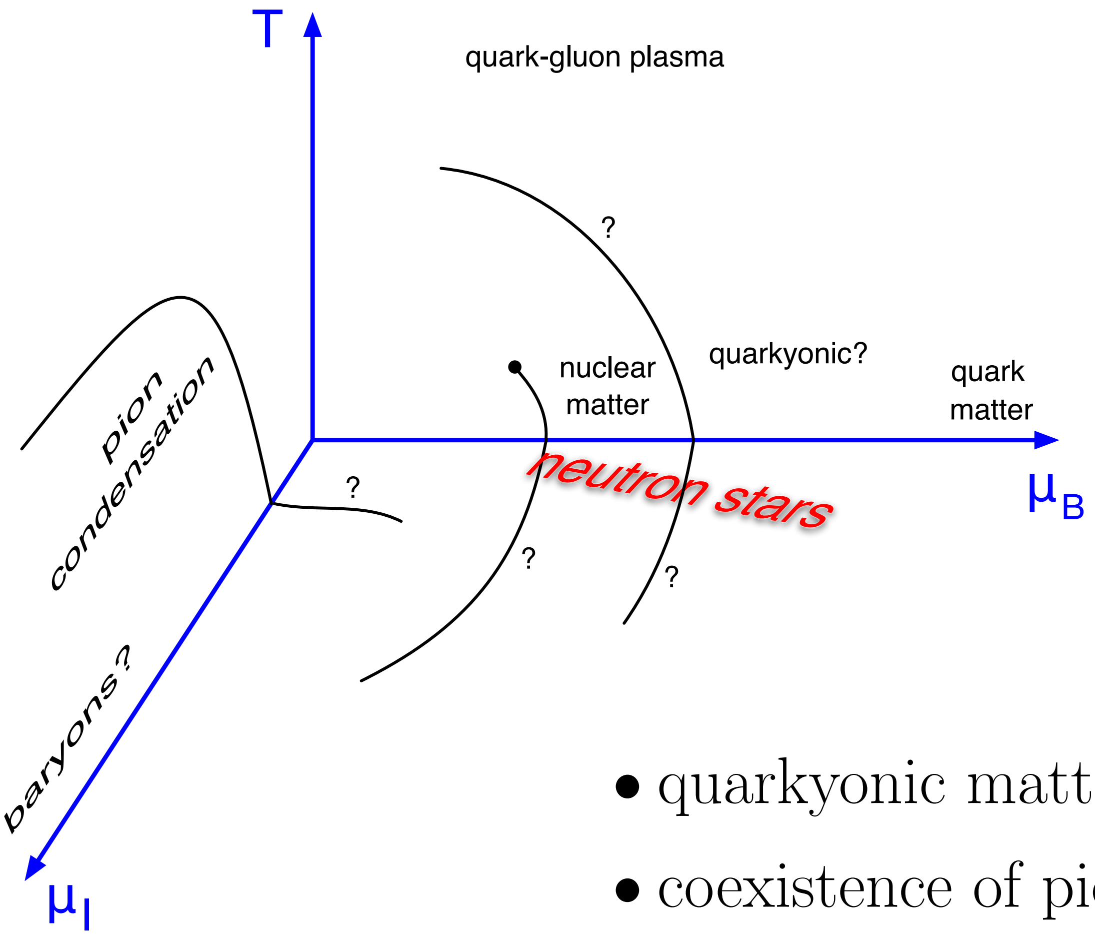
Building a realistic neutron star from holography

N. Kovensky, A. Schmitt, SciPost Phys. 11, 029 (2021)
N. Kovensky, A. Poole, A. Schmitt, Phys. Rev. D 105, 034022 (2022)
N. Kovensky, A. Poole, A. Schmitt, SciPost Phys. Proc. 6, 019 (2022)

- motivation and basics of Sakai-Sugimoto model
- isospin-asymmetric baryonic matter and pion condensation
- building a realistic neutron star from holography



Motivation: Phases of QCD and neutron stars



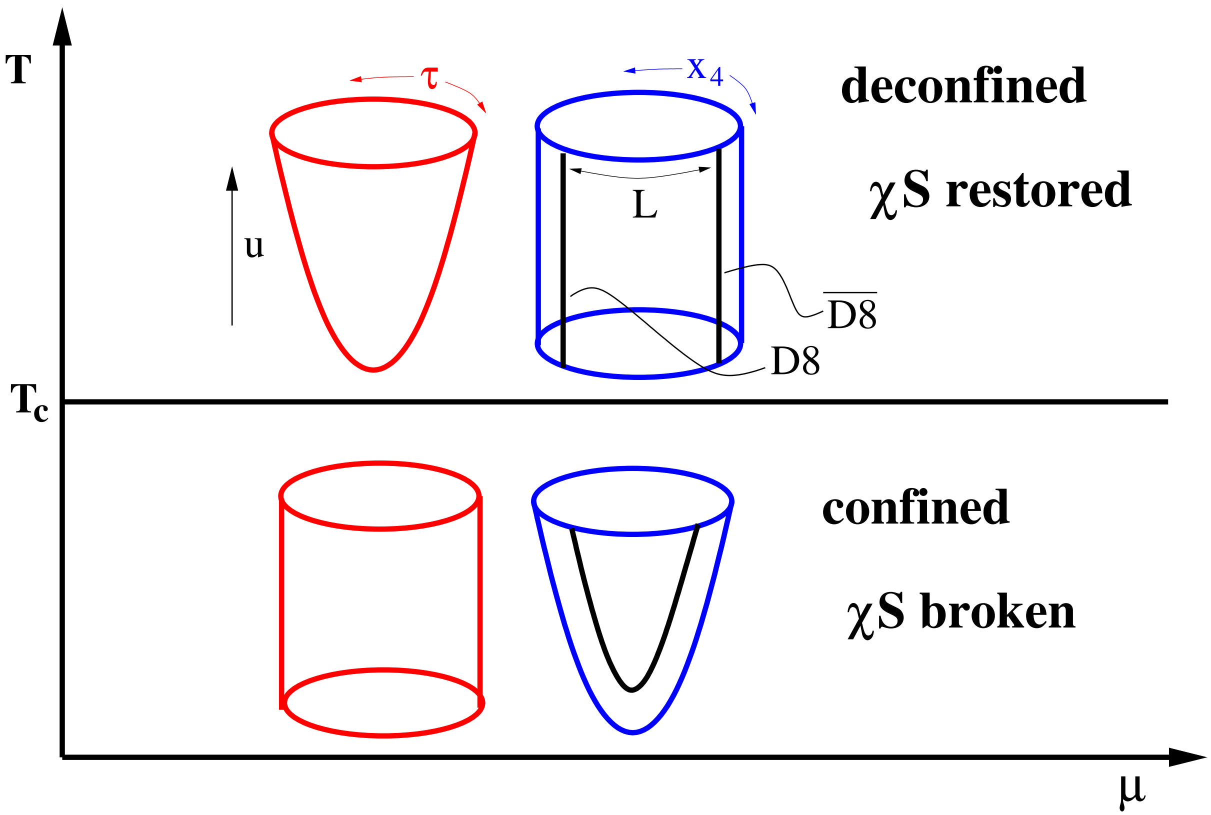
- quarkyonic matter for $N_c = 3$?
- coexistence of pion condensate and baryons?
- composition of neutron star matter?

Can holography help?

- dual of QCD: probably exists, but currently out of reach
- reliable strong-coupling calculation (usually infinite coupling)
- successful (qualitative) predictions for heavy-ion collisions (supersymmetric YM plasma instead of quark-gluon plasma)

- Sakai-Sugimoto model
  E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998)
  T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)
  - top-down approach with only 3 parameters
  - supersymmetry and conformal symmetry broken
  - dual to large-N_c QCD, however in inaccessible limit
  - successfully applied to meson, baryon, glueball spectra
    ... and phase structure, e.g., inverse magnetic catalysis
    F. Preis, A. Rebhan and A. Schmitt, JHEP 03, 033 (2011)

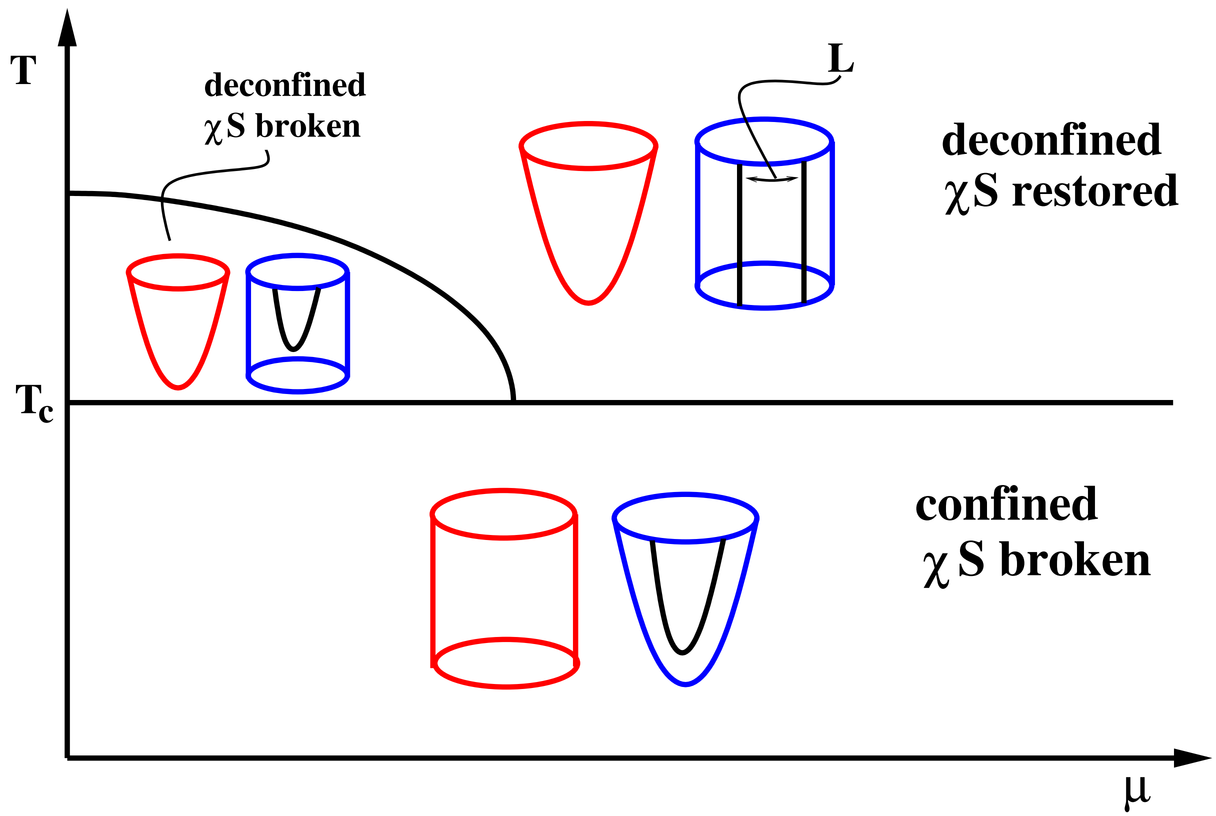
Phases in the Sakai-Sugimoto model (page 1/3)



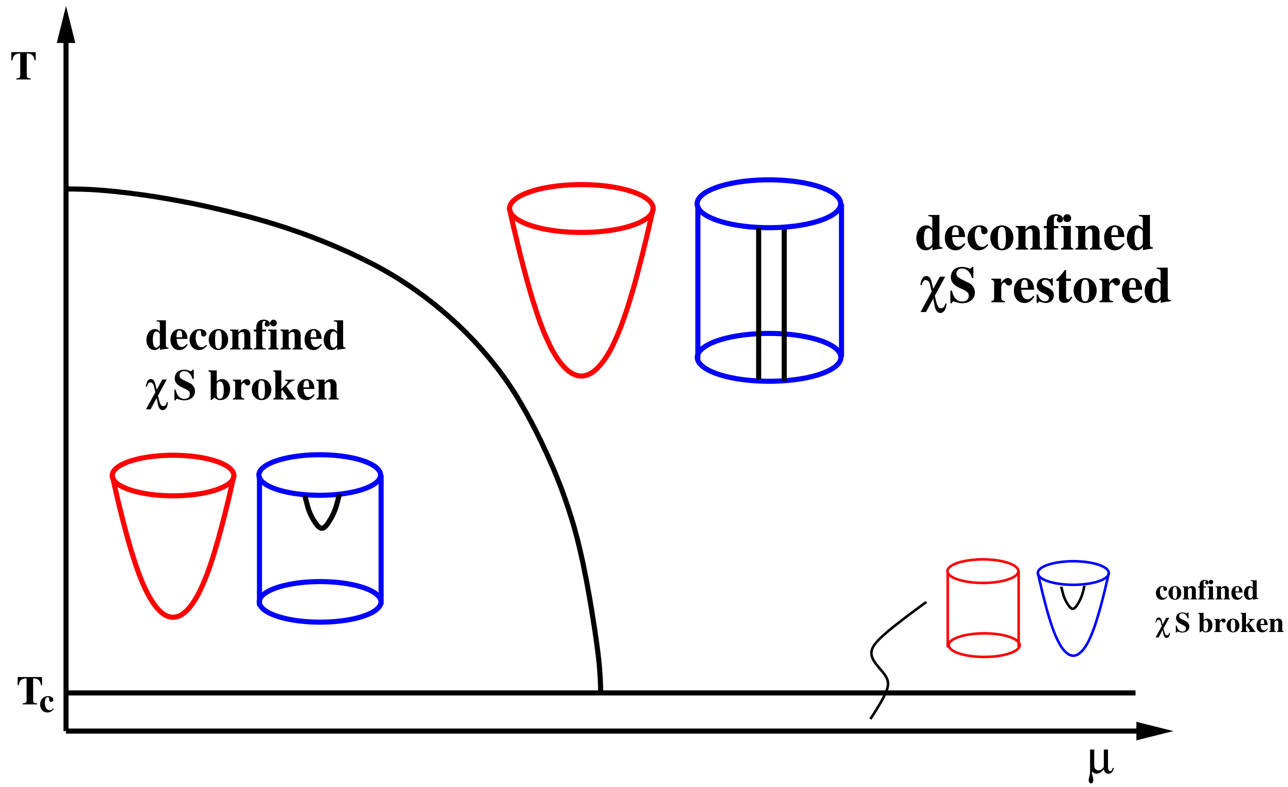
- in probe brane ("quenched") approximation: phase transition unaffected by quantities on flavor branes (μ, B, $\ldots$)
- not unlike expectation from large-N_c QCD

Phases in the Sakai-Sugimoto model (page 2/3)

- less "rigid" behavior for smaller L
- deconfined, chirally broken phase for $L < 0.3\,\pi/M_{\mathrm{KK}}$
  O. Aharony, J. Sonnenschein, S. Yankielowicz, Annals Phys. 322, 1420 (2007)
  N. Horigome, Y. Tanii, JHEP 0701, 072 (2007)



Phases in the Sakai-Sugimoto model (page 3/3)



- "decompactified" limit → gluon dynamics decouple
- "NJL-like" dual field theory

  E. Antonyan, J. A. Harvey, S. Jensen, D. Kutasov, hep-th/0604017

  J. L. Davis, M. Gutperle, P. Kraus, I. Sachs, JHEP 0710, 049 (2007)

  F. Preis, A. Rebhan and A. Schmitt, Lect. Notes Phys. 871, 51 (2013)

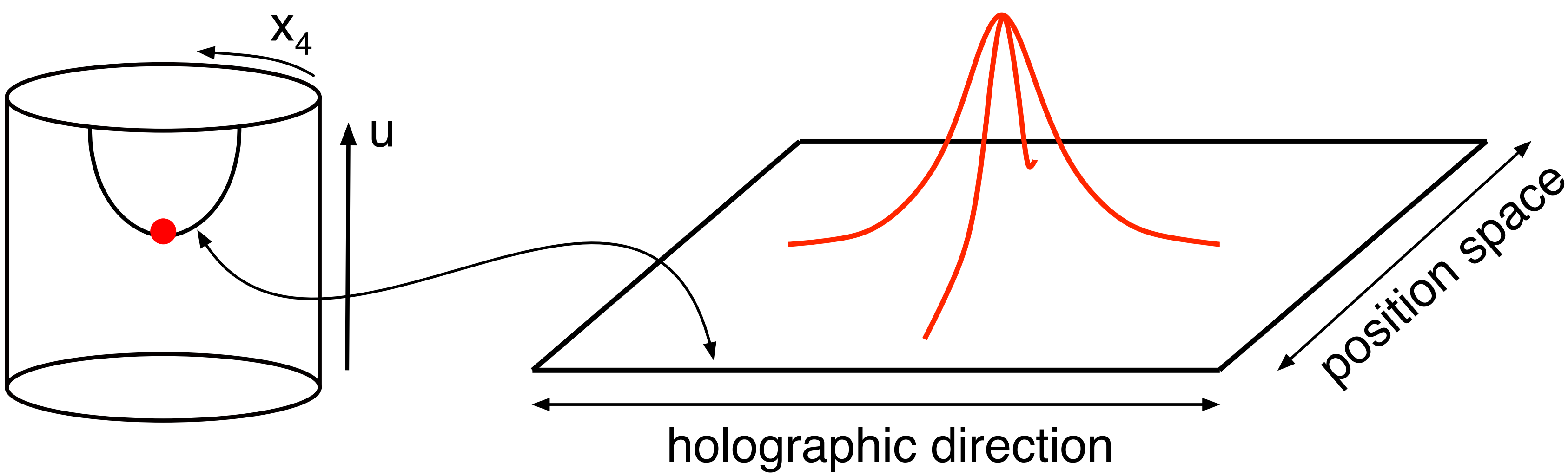
Background geometries as two different "models"

	deconfined geometry, decompactified limit	confined geometry, antipodal separation, DBI action $\simeq$ YM action
T-dependence	$\checkmark$	–
chiral phase transition	$\checkmark$	–
gluon dynamics	decoupled	relevant
numerics	difficult (D8-brane embedding!)	easy
used in the following for	isospin-asymmetric matter quarkyonic matter	isospin-asymmetric matter neutron stars

- baryons can be added in both geometries ...

Adding baryons

- baryons in AdS/CFT: wrapped D-branes with N_c string endpoints
  E. Witten, JHEP 9807, 006 (1998); D. J. Gross, H. Ooguri, PRD 58, 106002 (1998)
- baryons in Sakai-Sugimoto:
  – D4-branes wrapped on S^4
  – equivalently: instantons on D8-branes ($\rightarrow$ skyrmions)
  T. Sakai, S. Sugimoto, Prog. Theor. Phys. 113, 843-882 (2005)
  H. Hata, T. Sakai, S. Sugimoto, S. Yamato, Prog. Theor. Phys. 117, 1157 (2007)



Approximations for holographic nuclear matter

- Pointlike approximation
  O. Bergman, G. Lifschytz, M. Lippert, JHEP 0711, 056 (2007)
  quarkyonic matter: N. Kovensky and A. Schmitt, JHEP 09, 112 (2020)

- Finite-width instantons
  - Non-interacting
    K. Ghoroku, K. Kubo, M. Tachibana, T. Taminato and F. Toyoda, PRD 87, 066006 (2013)
    S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)
    F. Preis, A. Schmitt, JHEP 1607, 001 (2016); EPJ Web Conf. 137, 09009 (2017)
  - Two-body interactions from exact two-instanton solution
    K. Bitaghsir Fadafan, F. Kazemian, A. Schmitt, JHEP 1903, 183 (2019)

- "Homogeneous ansatz" (not based on single-instanton solution)
  M. Rozali, H. H. Shieh, M. Van Raamsdonk and J. Wu, JHEP 0801, 053 (2008)
  S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)
  M. Elliot-Ripley, P. Sutcliffe and M. Zamaklar, JHEP 1610, 088 (2016)
  with isospin asymmetry: N. Kovensky and A. Schmitt, SciPost Phys. 11, 029 (2021)

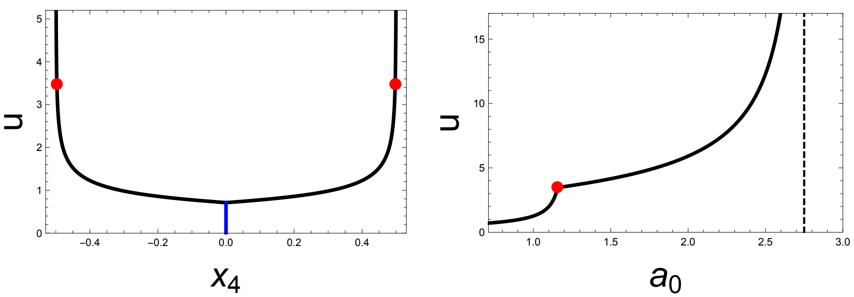
Results

- quarkyonic matter (only results)
- isospin-asymmetric baryonic matter (formalism + results)
- neutron stars (construction + results)

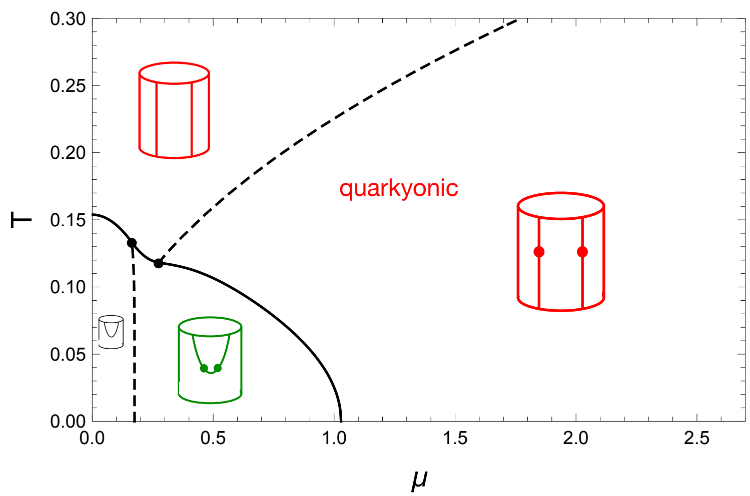
Holographic quarkyonic matter

N. Kovensky and A. Schmitt, JHEP 09, 112 (2020)

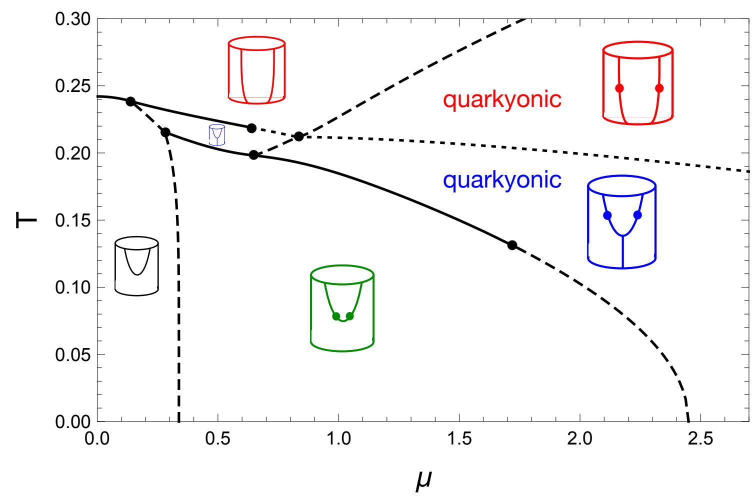
large-N_c QCD L. McLerran and R. D. Pisarski, NPA 796, 83 (2007)



quarks and baryons separated in holographic direction



$m_\pi = 0$



$m_\pi > 0$

Isospin-asymmetric matter: setup (page 1/2)

- D8-brane action

$$S = \underbrace{T_8 V_4 \int_{x^\mu}\int_z e^{-\Phi}\sqrt{\det(g+2\pi\alpha' F)}}_{\text{Dirac-Born-Infeld (DBI)}} + \underbrace{\frac{N_c}{8\pi^2}\int_{x^\mu}\int_z \hat{A}_0 \mathrm{Tr}[F_{ij}F_{kz}]\epsilon_{ijk}}_{\text{Chern-Simons (CS)}}$$

- gauge fields in the bulk ($\to$ global symmetry at the boundary)

$$N_f = 2: \qquad F_{\mu\nu} = \hat{F}_{\mu\nu} + F^a_{\mu\nu}\sigma_a$$

- baryon chemical potential

$$\mu_B = \hat{A}_0(z = \pm\infty)$$

- (topological) baryon number

$$N_B = -\frac{1}{8\pi^2}\int_{\vec{x}}\int_z \mathrm{Tr}[F_{ij}F_{kz}]\epsilon_{ijk}$$

Isospin-asymmetric matter: setup (page 2/2)

- include isospin chemical potential

$$(\pm)\mu_I = A_0^3(z = \pm\infty)$$

- allow for pion condensation ($\to$ different boundary conditions)
  O. Aharony, K. Peeters, J. Sonnenschein and M. Zamaklar, JHEP 02, 071 (2008)
- assume $m_\pi = 0$ ($m_\pi > 0$: work in progress)
- homogeneous ansatz for non-abelian gauge fields
  M. Rozali, H. H. Shieh, M. Van Raamsdonk and J. Wu, JHEP 0801, 053 (2008)

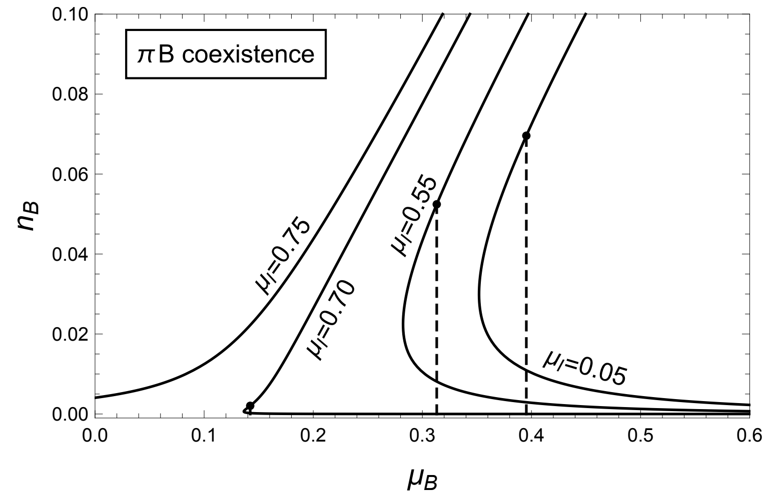
$$A_i(z) = h(z)\sigma_i$$

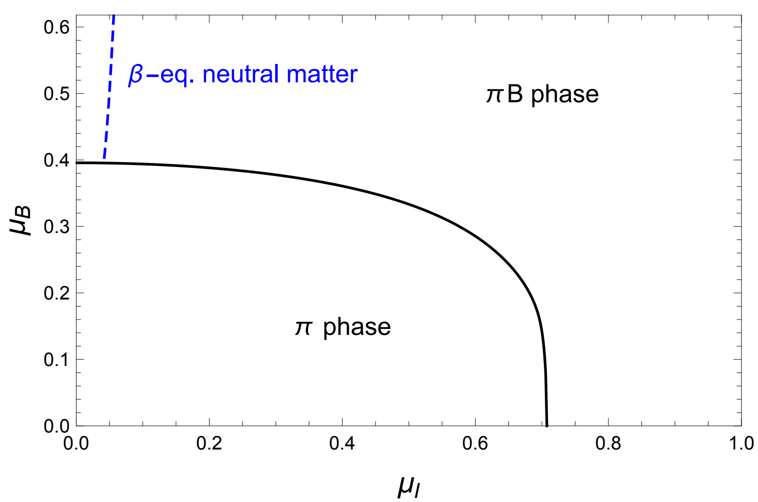
$\to$ solve classical EOMs for $\hat{A}_0$, A_0^3, h (and x_4) for given μ_B, μ_I, T

$\to$ compare free energies of vacuum, pion condensed phase, baryonic phase, coexistence phase (and chirally symmetric phase)

Isospin-asymmetric matter: results (page 1/2)

- confined geometry, antipodal branes, YM approximation
- first-order transition from pion to coexistence phase

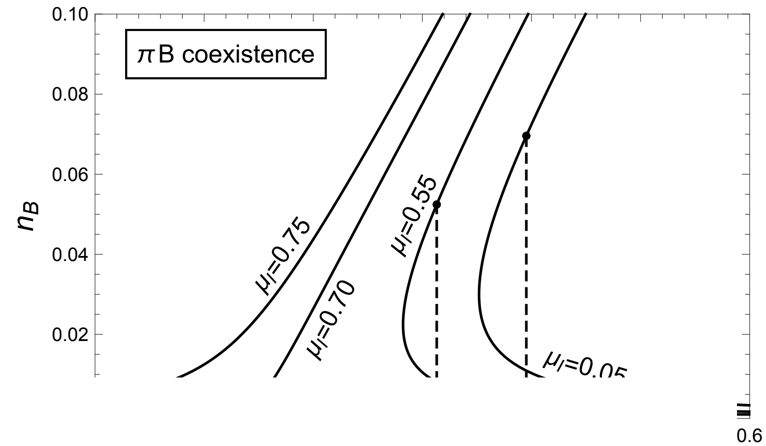


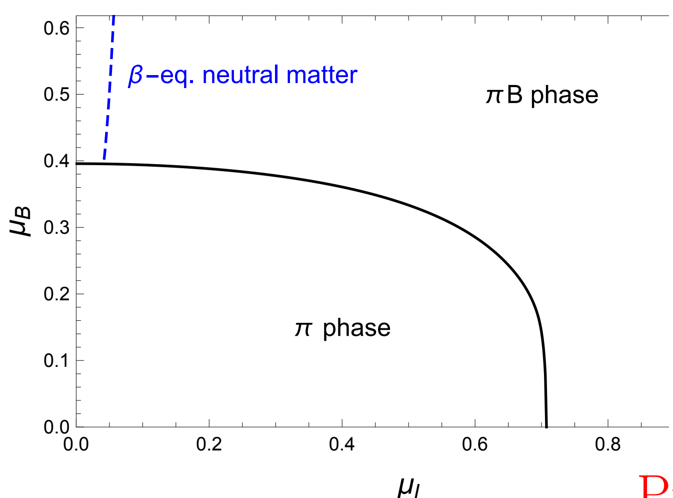


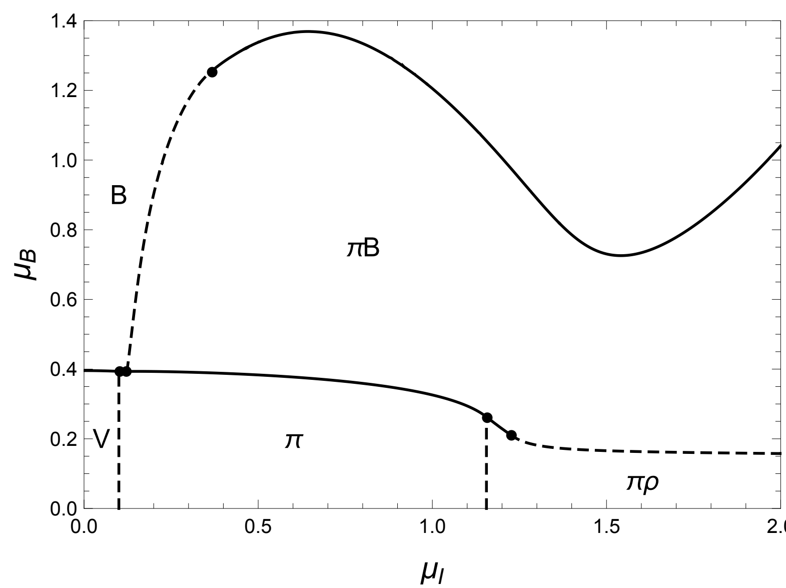
- pion condensate coexists with baryonic matter

Isospin-asymmetric matter: results (page 1/2)

- confined geometry, antipodal branes, YM approximation
- first-order transition from pion to coexistence phase





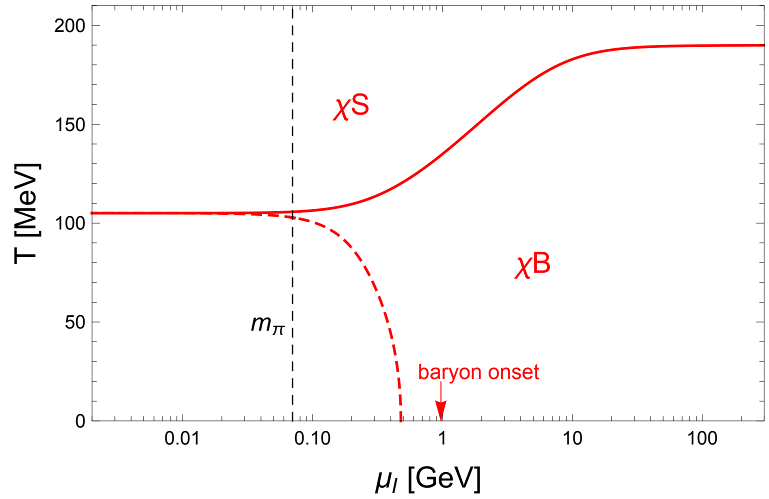


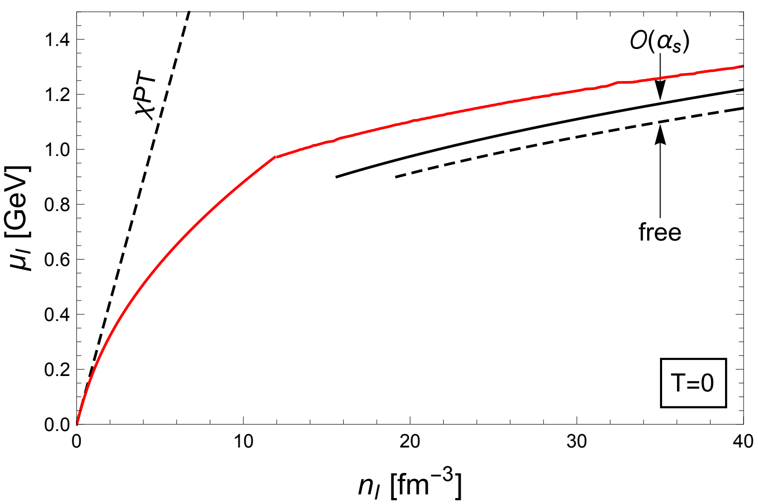
Preliminary: physical m_π and improved A_i ansatz

N. Kovensky, A. Poole, A. Schmitt, work in progress

Isospin-asymmetric matter: results (page 2/2)

- deconfined geometry, decompactified limit

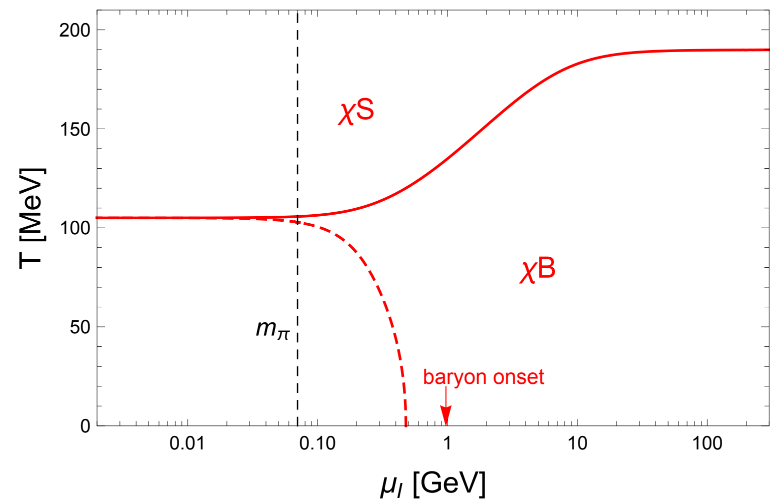


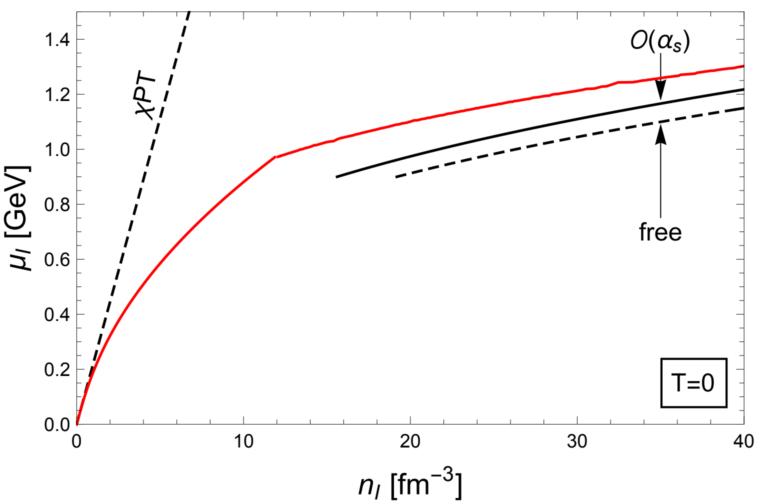


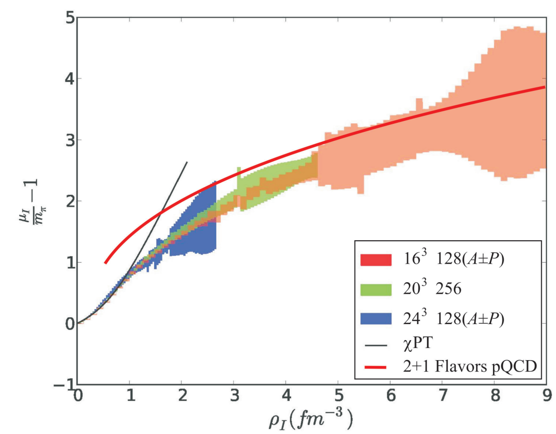
- interpolate between chiral perturbation theory and pQCD?

Isospin-asymmetric matter: results (page 2/2)

- deconfined geometry, decompactified limit



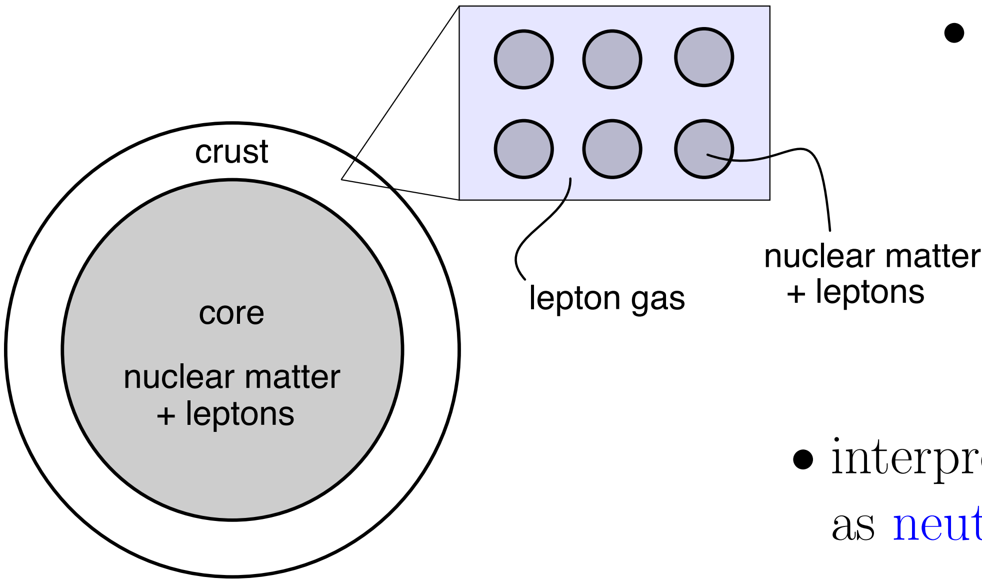




T. Graf *et al.*, PRD 93, 085030 (2016)

W. Detmold *et al.*, PRD 86, 054507 (2012)

Building a neutron star from holography (page 1/4)

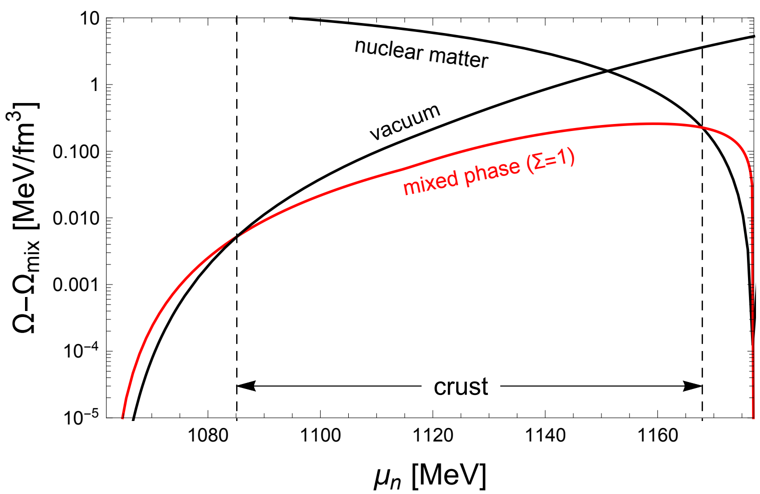


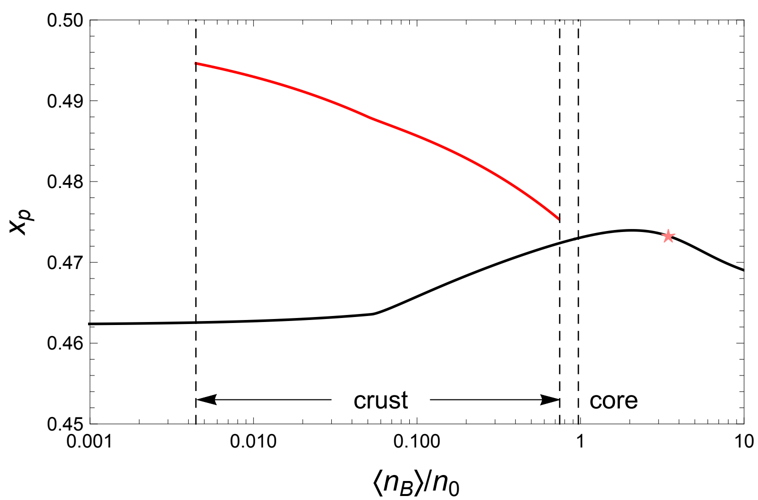
- add leptons (electrons + muons) to holographic nuclear matter (neglect pion condensation)
- interpret holographic isospin components as neutron and proton
- construct uniform (locally neutral) and mixed (globally neutral) phases in β-equilibrium
- use Wigner-Seitz approximation and step-like interfaces (surface tension Σ as input)

dynamic calculation of clusters and crust-core transition

Building a neutron star from holography (page 2/4)

- mixed phase energetically preferred for small μ_n



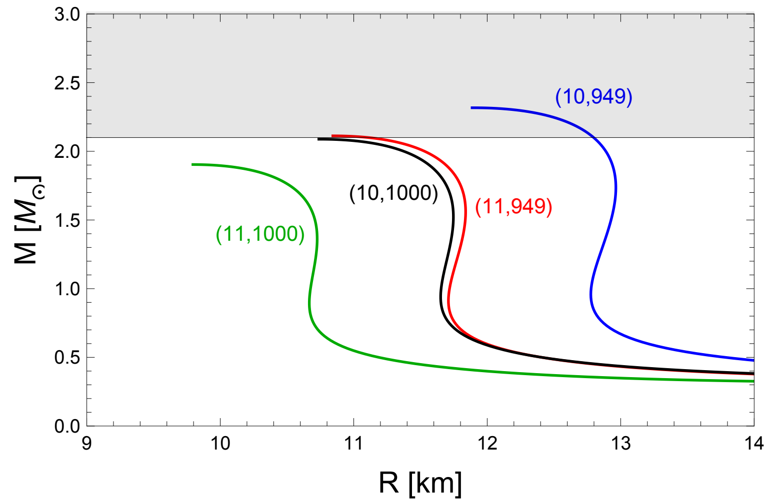


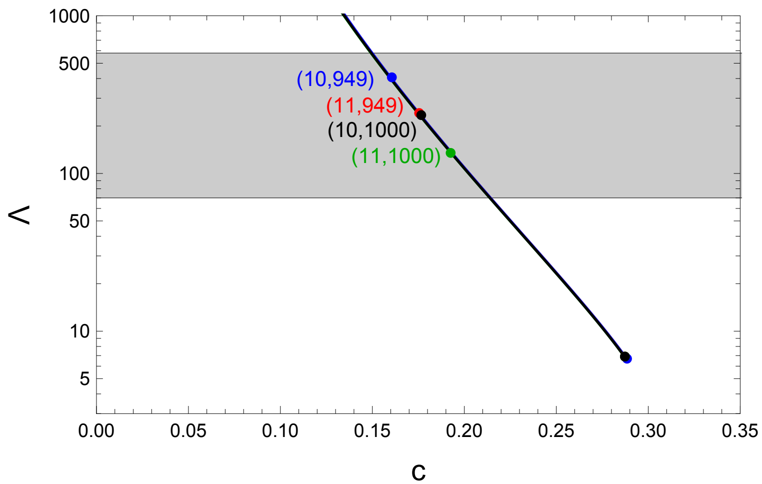
- large-N_c artifact:
  continuous isospin spectrum
  → large proton fraction
  → muons in inner crust

Building a neutron star from holography (page 3/4)

couple to gravity ("TOV equations") → mass-radius curves
for different parameter pairs (λ, M_{KK}) with $\Sigma = 1\,\text{MeV/fm}^2$

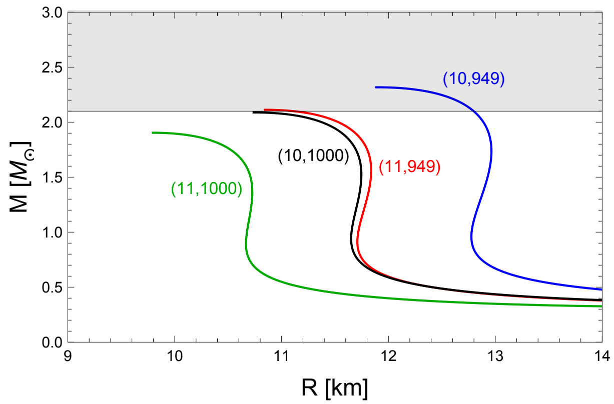
fit to	λ	M_{KK}
f_π, m_ρ	16.63	949 MeV
σ, m_ρ	12.55	949 MeV
n_0, E_B	7.09	1000 MeV

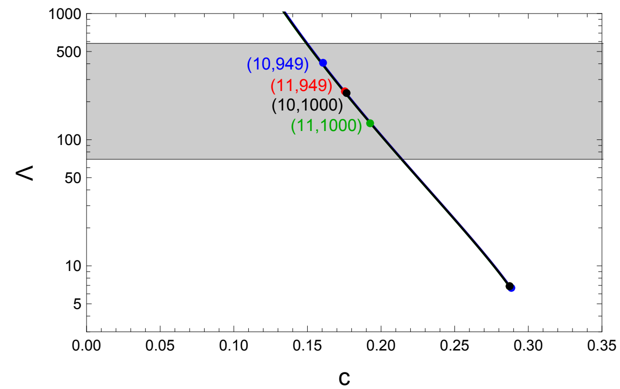




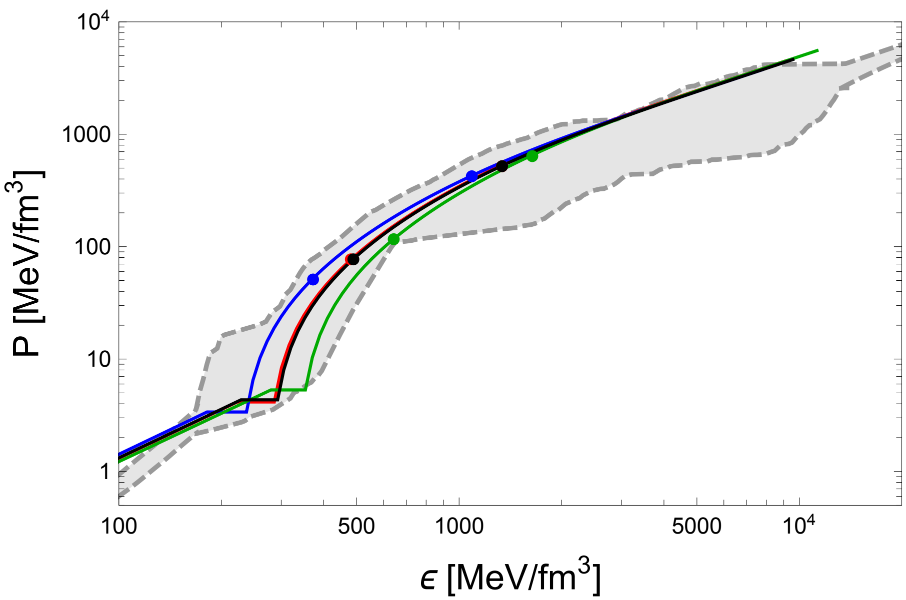
- realistic maximal masses and 1.4-solar-mass deformabilities

Building a neutron star from holography (page 3/4)



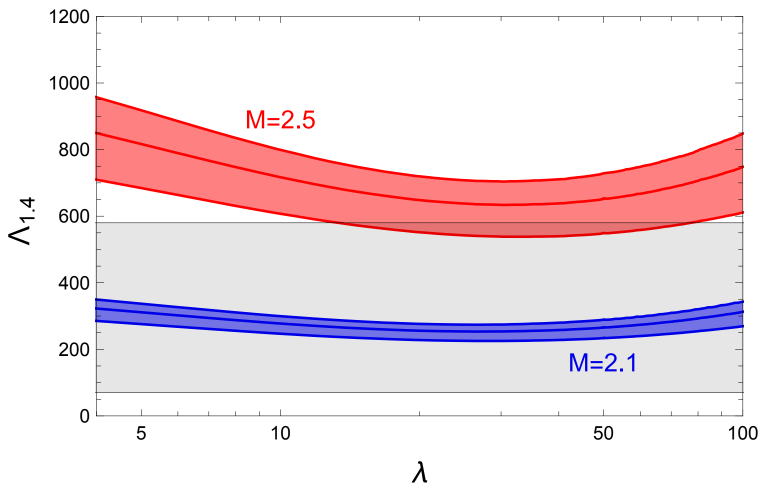


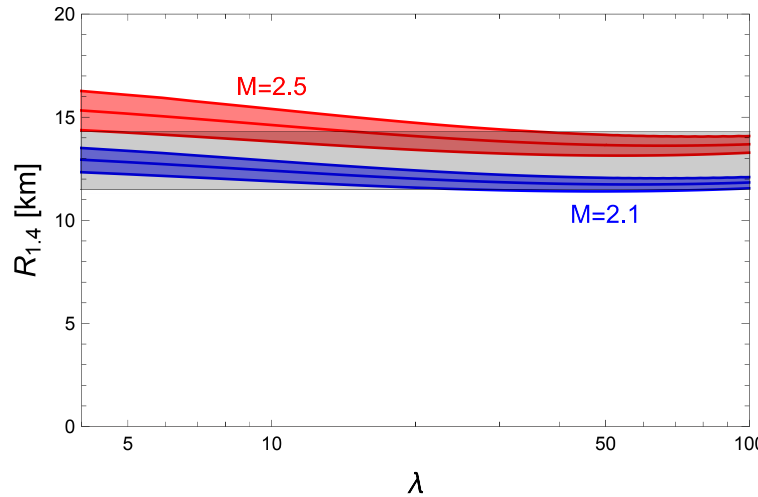
Can our results be connected to perturbative QCD?



grey band taken from E. Annala, T. Gorda, A. Kurkela, and A. Vuorinen, PRL 120, 172703 (2018)

Building a neutron star from holography (page 4/4)





- astrophysical constraints from GW170817 + NICER
- 2.5-solar-mass stars barely possible
- parameter-independent prediction for lower bounds on $\Lambda_{1.4}$ and radius $R_{1.4}$

  more systematic predictions: N. Kovensky, A. Poole and A. Schmitt, SciPost Phys. Proc. 6, 019 (2022)

other holographic approaches to compact stars (combined with "traditional" methods), see reviews
M. Järvinen, EPJC 82, 282 (2022)
C. Hoyos, N. Jokela and A. Vuorinen, Prog. Part. Nucl. Phys. 126, 103972 (2022)

Summary

- holographic Sakai-Sugimoto model gives a "QCD-like" theory with all necessary ingredients
  (chiral transition, baryons, pion condensation, ...)

- introducing isospin-asymmetric baryonic matter allows us to
  - study phase structure for finite μ_B, μ_I, T
  - construct neutron stars from a single model
    (unlike most other holographic and non-holographic approaches)

Outlook

- improve holographic description of baryons (large-N_c artifacts?)
- improve holographic crust (pasta structures, inner crust)
- include pion mass in phase structure with isospin
  N. Kovensky, A. Poole, A. Schmitt, in preparation
- include magnetic field
  pointlike baryons: F. Preis, A. Rebhan and A. Schmitt, JPG 39, 054006 (2012)
- compute surface tension dynamically
- include strangeness ($SU(3)$ gauge theory in the bulk
  $\rightarrow$ holographic hyperons in compact stars?)
- holographic quark-hadron (quarkyonic-hadron) phase transition in compact stars?